Special Topics on Basic EECS I
VLSI Devices
Lecture 9

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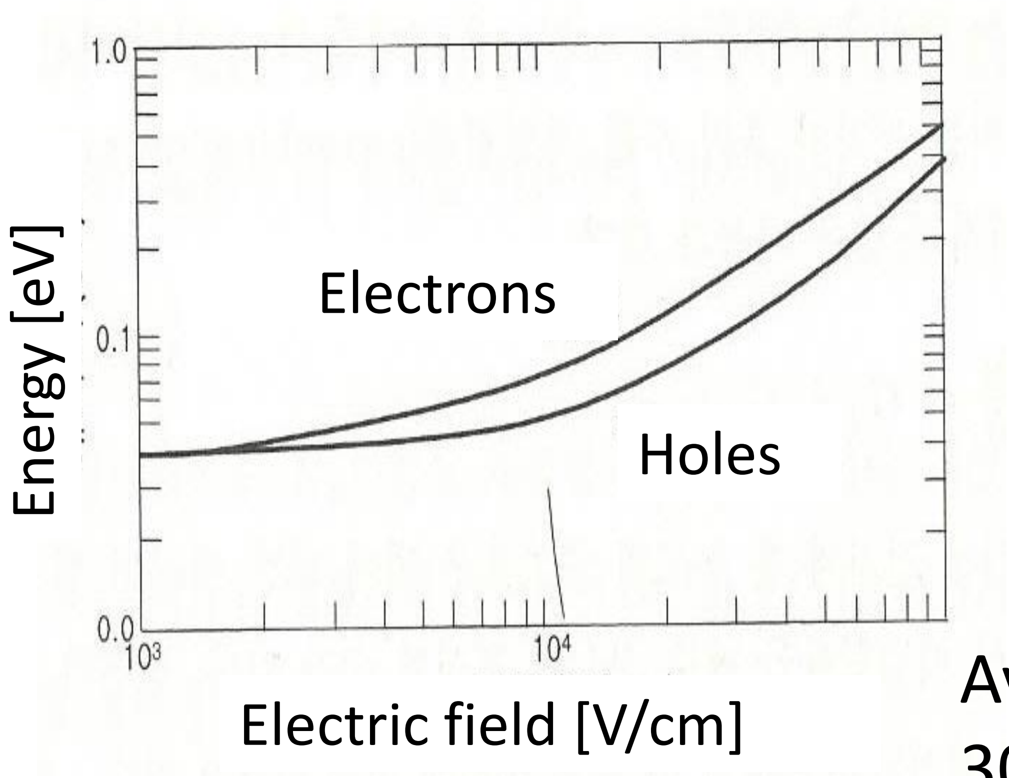
Hot electron

- Not only velocity, but also energy…
  - Increases when the electric field increases.
  - Increase of energy is a reason of the velocity saturation. *Why?*



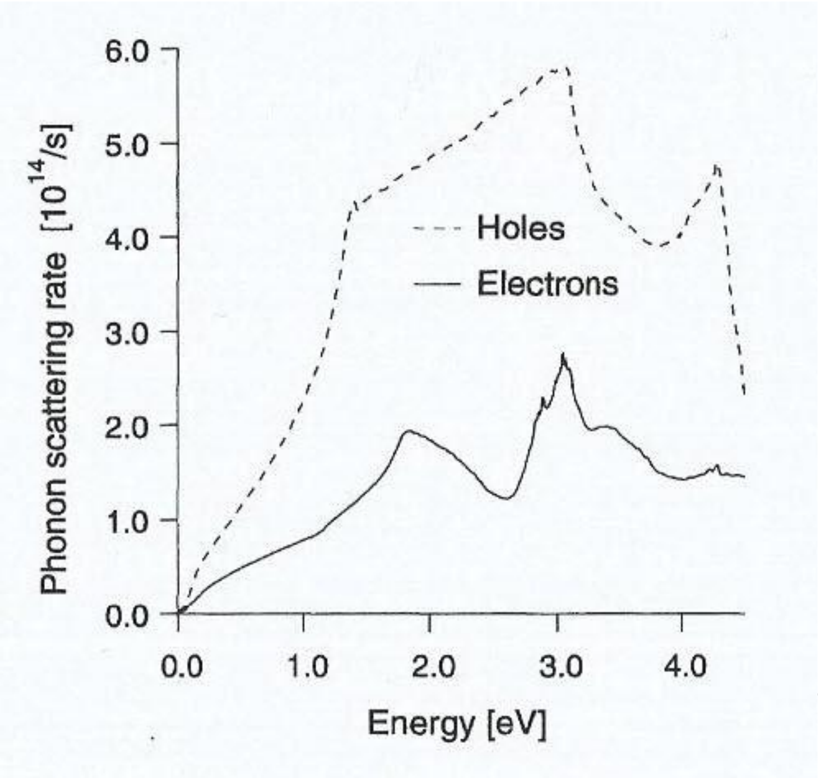
Up to 1 kV/cm, average energy is almost the same with the lattice energy.

Above 10 kV/cm, average energy significantly deviates from the lattice energy.

Average energy of electrons/holes in Si at 300K (Park's book)

Velocity saturation

- Electron with higher energy
  - Has a higher chance to be scattered by phonons. (Higher DOS)
  - More frequent scattering : Smaller τ_m

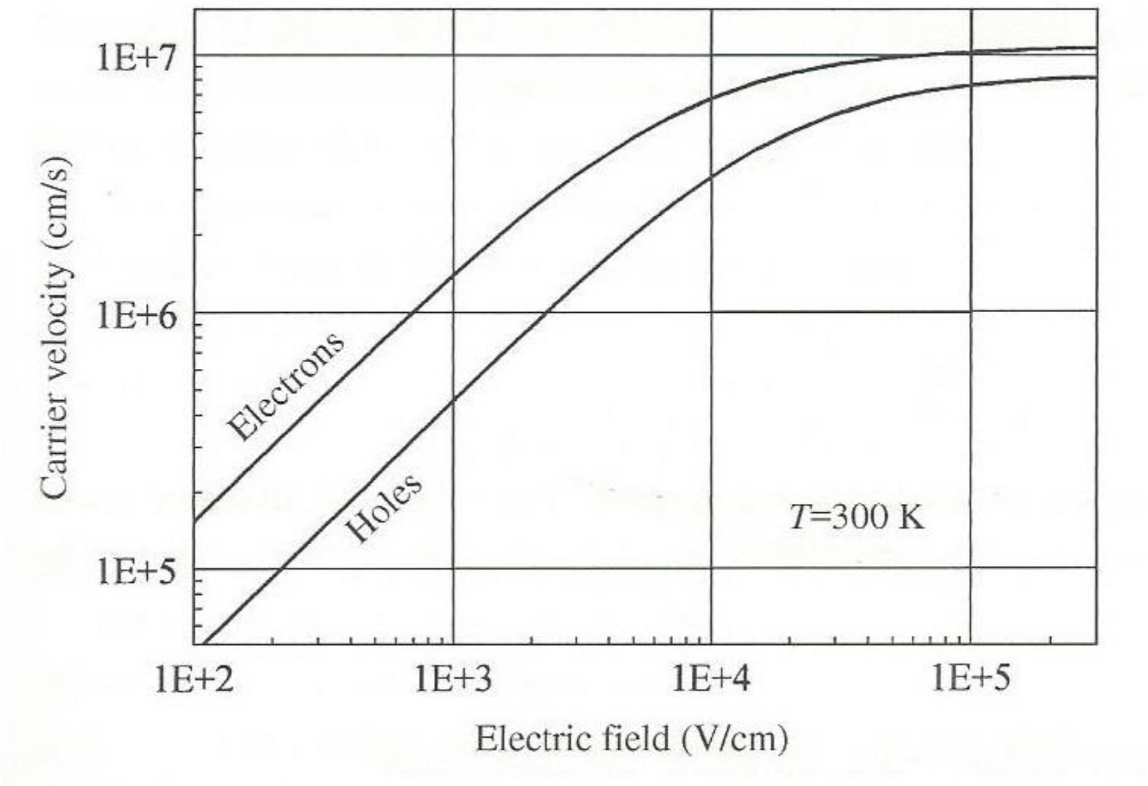


Phonon scattering rate in Si resembles the Density-Of-States.

Phonon scattering rate in Si (Jungemann's book)

Velocity vs. electric field

- At low electric fields, the linear relationship is valid.
  - At high electric fields, the velocity saturation starts to occur. The saturation velocity of Si is about 10^7 (cm/sec).



Velocity-field relationship in Si at 300K (Taur's book)

Caughey-Thomas relation

- For silicon,
  - Electron velocity can be approximated by

$$v_n = \frac{v_s}{\left[1 + \left(\frac{E_{on}}{E}\right)^2\right]^{0.5}}$$

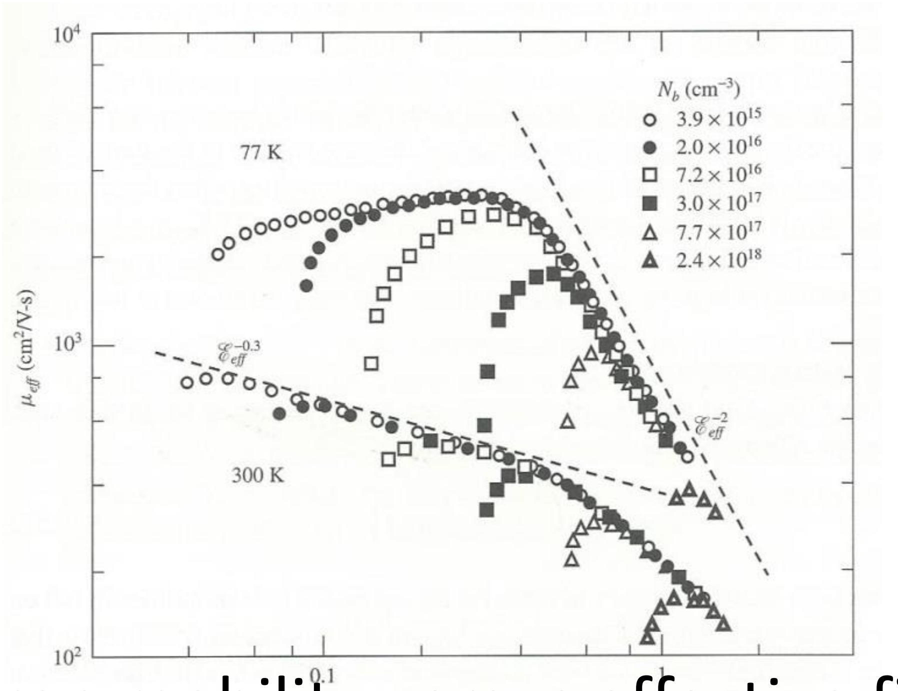
  - Hole velocity

$$v_p = \frac{v_s}{\left[1 + \left(\frac{E_{op}}{E}\right)\right]}$$

  - Why are they different?

Other scattering mechanisms

- We have discussed about the bulk mobility.
  - Other scattering mechanisms (alloy scattering & impact ionization)
  - Surface scattering severely reduces the inversion mobility.



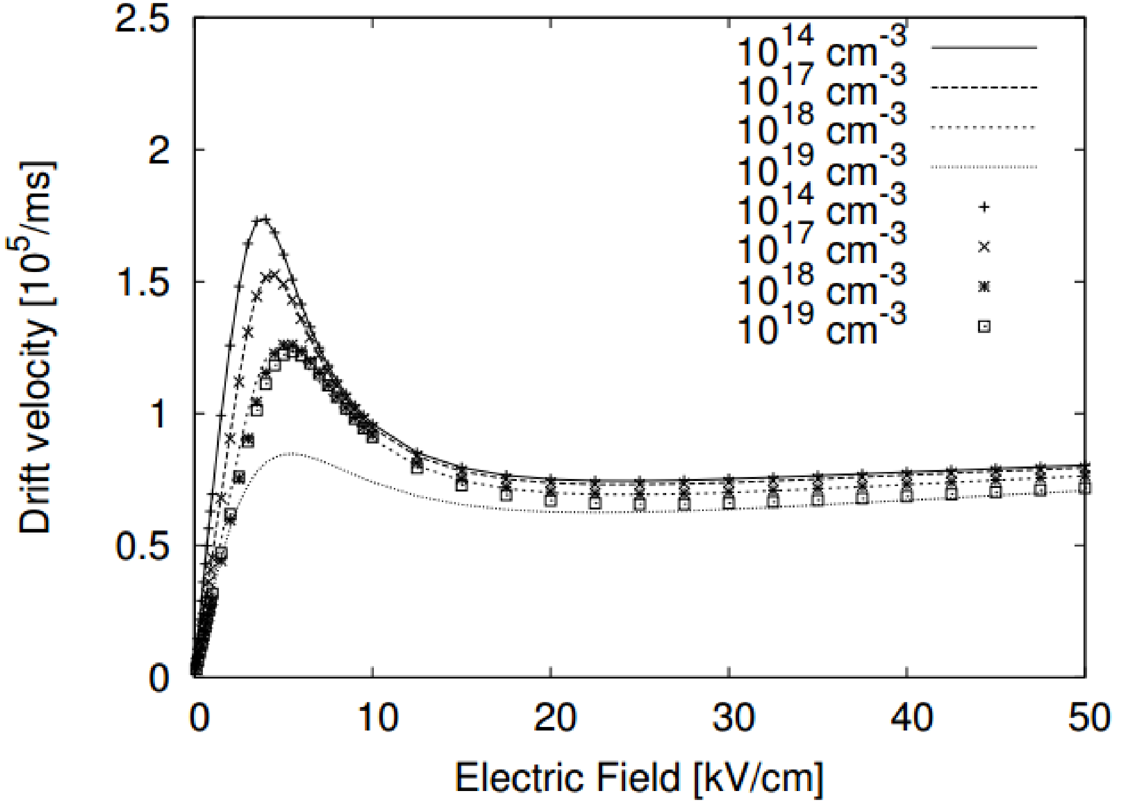
So-called "universal" mobility curve in the Si inversion layer.

Two difference contributions are clearly visible.

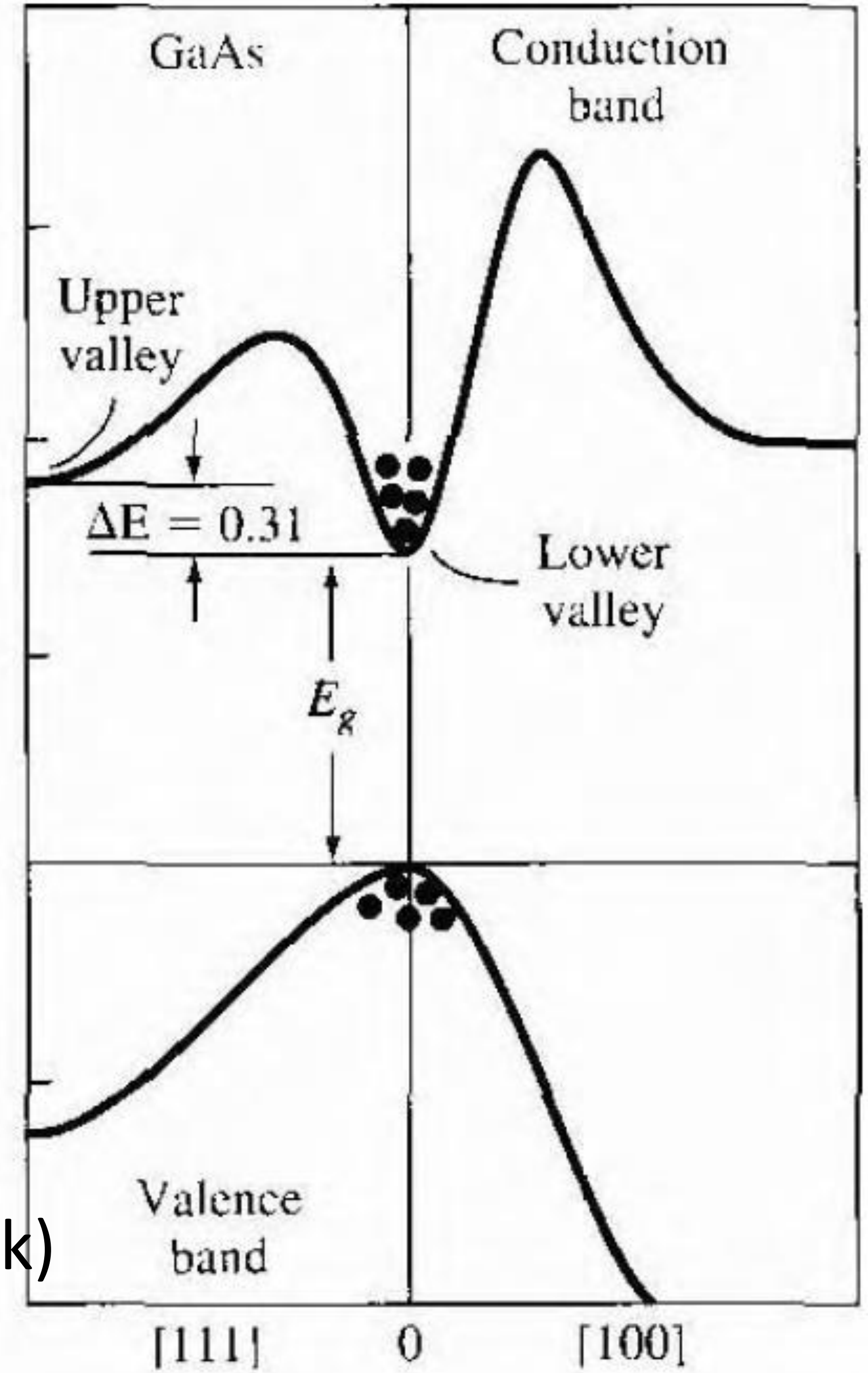
Electron mobility versus effective field for several doping concentrations (Takagi's paper)

GaAs case

- Negative differential mobility
  - Its L valley is heavy.



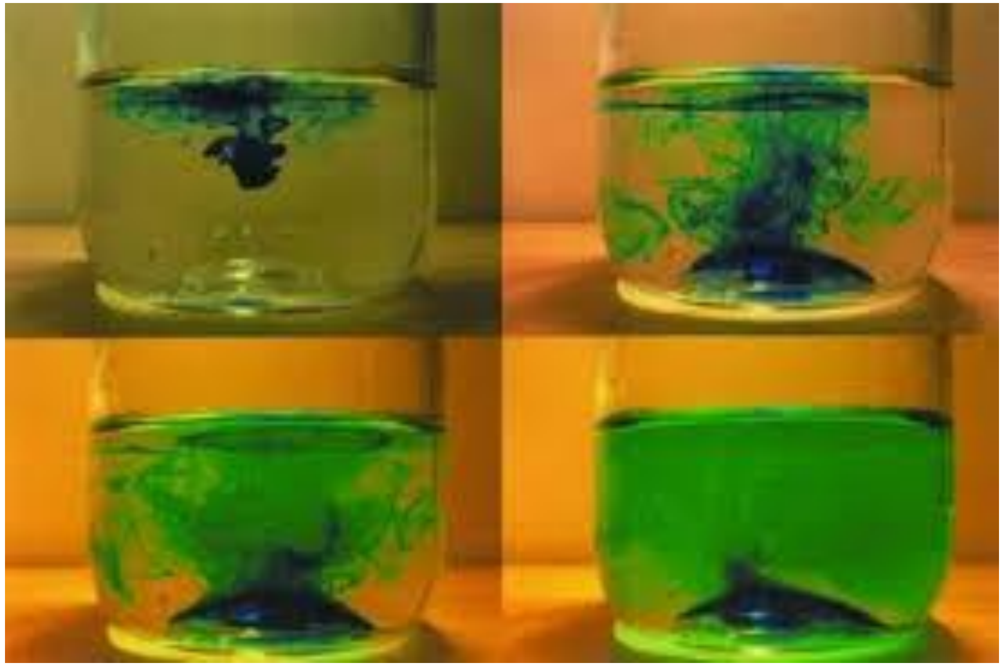
(J. Bieder et al., IWCE 2010)



(Neamen's book)

Diffusion

- It is not only for charged particles.
  - For example,



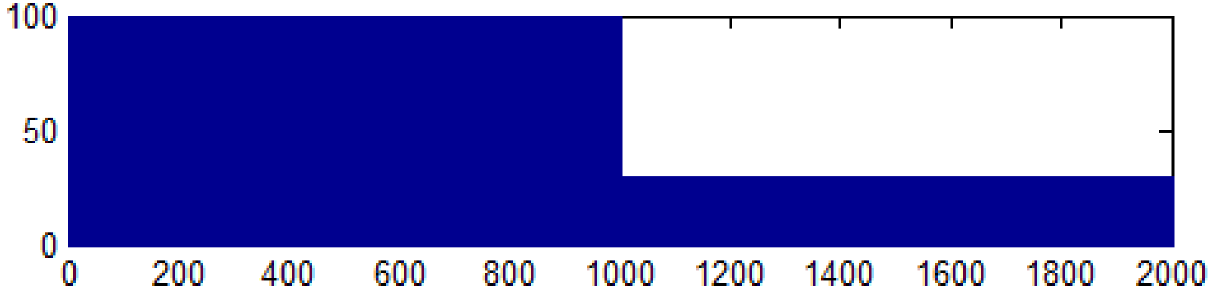
Diffusion of ink
(Google images)

  - Therefore, no polarity is expected.

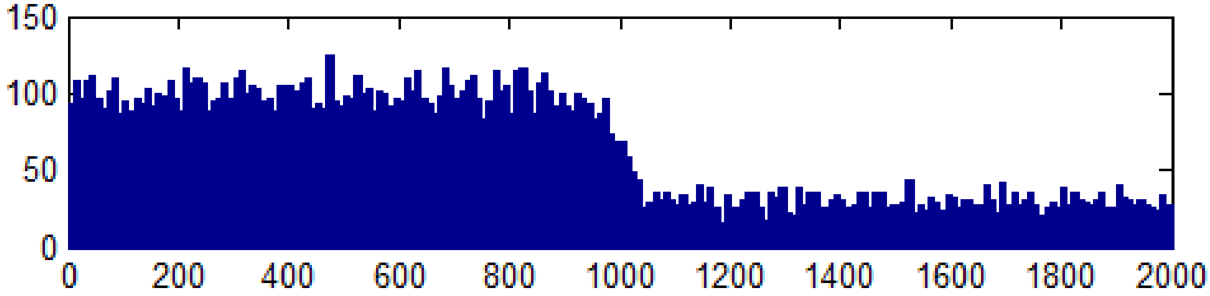
A simple game, again

- Random motion of balls in a 1D box
  - At each turn, they can move forward (+1) or backward (-1).

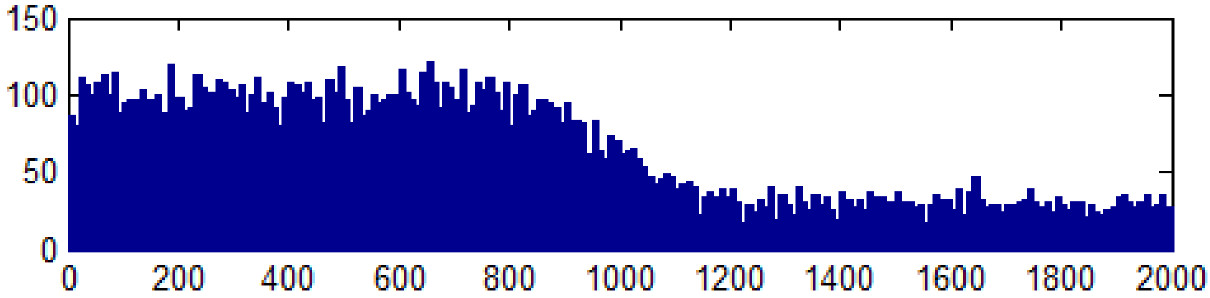
Initial condition



1 k turns



10 k turns



Equation

- Flux
  - The electron flux due to the diffusion mechanism is given by

$$\mathbf{F}_n = -D_n \nabla n$$

  where D_n is the electron diffusion coefficient in the unit of (cm^2/sec).
  - The diffusion current density is

$$\mathbf{J}_{n,diff} = qD_n \nabla n$$

Taur, Eq. (2.36)

- How about the hole?
  - The diffusion current density is

$$\mathbf{J}_{p,diff} = -qD_p \nabla p$$

Taur, Eq. (2.37)

An example

- Taken from Neamen's book
  - Over 1 mm, the electron density varies linearly from $1X10^{18}$ cm^{-3} to $7X10^{17}$ cm^{-3}.
  - The diffusion coefficient is D_n = 225 cm2/sec.
  - Calculate the current density.

$$J_n = +qD_n \frac{dn}{dx}$$

$$= (1.6 \times 10^{-19}\ \mathrm{C})(225\ \mathrm{cm^2/s}) \left(\frac{1 \times 10^{18}\ \mathrm{cm^{-3}} - 7 \times 10^{17}\ \mathrm{cm^{-3}}}{0.1\ \mathrm{cm}} \right)$$

$$= 108\ \mathrm{A/cm^2}$$

Revisit the total current density.

- Total current density
  - Electron current density

$$\mathbf{J}_n = q\mu_n n\mathbf{E} + qD_n \nabla n$$ Taur, Eq. (2.54)

  - Hole current density

$$\mathbf{J}_p = q\mu_p p\mathbf{E} - qD_p \nabla p$$ Taur, Eq. (2.55)

  - (Time-dependent) displacement current density

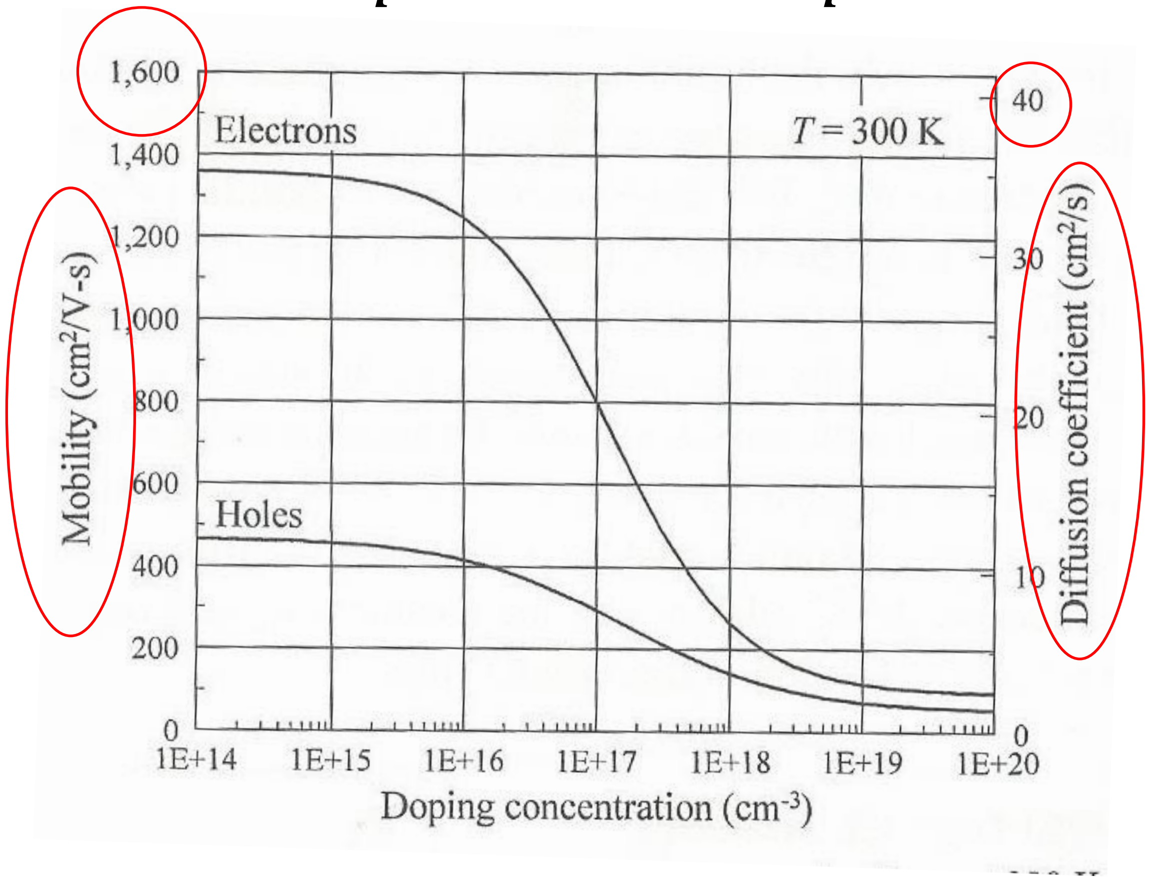
$$\mathbf{J}_{displacement} = \frac{\partial}{\partial t}(\epsilon \mathbf{E})$$

Einstein relation

- At equilibrium, we have the following relations:

$$D_n = \frac{k_B T}{q}\mu_n, D_p = \frac{k_B T}{q}\mu_p$$

Taur, Eq. (2.38) and Eq. (2.39)



(Park's book)

Poisson equation

- Electrostatic potential, ϕ (In Taur, it is denoted as ψ_i.)
  - Conventionally, it is defined in terms of the intrinsic Fermi level,

$$E_i = -q\phi$$

Taur, Eq. (2.40)

- Electric field, $\mathbf{E}$
  - It is equal to the negative gradient of ϕ,

$$\mathbf{E} = -\nabla\phi$$

Taur, Eq. (2.41)

- Poisson equation

$$\nabla \cdot \mathbf{D} = \nabla \cdot (\epsilon \mathbf{E}) = \rho$$

$$\rho = q(p - n + N_d^+ - N_a^-)$$

  - One dimensional and homogeneous system

$$\frac{d^2\phi}{dx^2} = -\frac{\rho}{\epsilon}$$

Taur, Eq. (2.42)

Boundary condition

- Tangential field
  - Tangential fields are continuous.

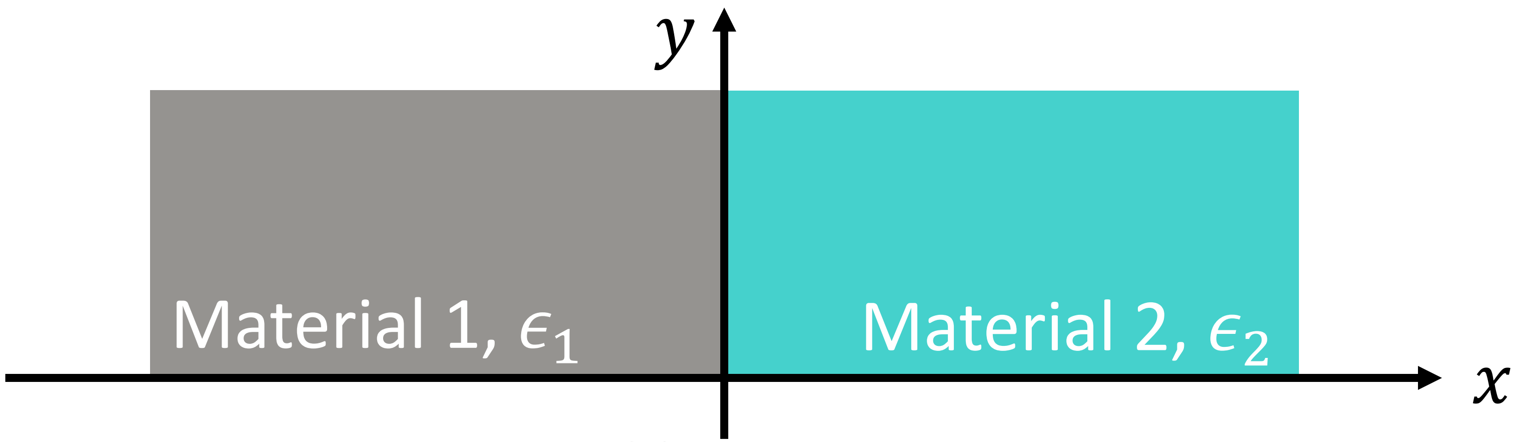
$$E_{1y}(0, y) = E_{2y}(0, y)$$

Taur, Eq. (2.46)

- Normal field
  - Perpendicular component of is continuous.

$$\epsilon_1 E_{1x}(0, y) = \epsilon_2 E_{2x}(0, y)$$

Taur, Eq. (2.47)



Revisiting carrier concentrations

$$E_f = -q\phi_f$$

- Carrier densities are expressed as

$$n = n_i \exp\left(-\frac{E_i - E_f}{k_B T}\right) = n_i \exp\left(\frac{\phi - \phi_f}{\frac{k_B T}{q}}\right) \quad \text{Taur, Eq. (2.49)}$$

$$p = n_i \exp\left(\frac{E_i - E_f}{k_B T}\right) = n_i \exp\left(-\frac{\phi - \phi_f}{\frac{k_B T}{q}}\right) \quad \text{Taur, Eq. (2.50)}$$

  – These relations are generally applicable in the presence of net charge and band bending.

Thank you!